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We had previously written a Final Report for this award on August 1, 2001. At that time we provided ARO, as Appendix to Final Report, with three copies of the book "RF Technologies for Low Power Wireless Communications". Due to administrative reasons, we requested and were granted an extended contractual period to January 31, 2002. This period was used only to complete the last remaining technical activity that was carried out by the group of T. Itoh in the area of Active Integrated Antennas based on GaN transistor.

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SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Tatsuo Itoh
Professor
University of California, Los Angeles

FINAL REPORT FOR MURI PROJECT

Low Power/Low Noise Electronics Technologies for Wireless Communications

University of California, Los Angeles
University of California, San Diego

Date: **January 31, 2002**

Supported by: **ODDR&E**

Monitored by: **ARO Electronics Division**
DAAH04-96-1-0005

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INTRODUCTION AND BACKGROUND

We have previously written Final Repor for this award on August 1, 2001. In addition, we provided ARO, as Appendix to Final Report, with three copies of the book “RF Technologies for Low Power Wireless Communications,” edited by T. Itoh, G. Haddad and J. Harvey and published by Wiley-Interscience.

Due to administrative reasons, we need to extend contractual peiod to January 21, 2002. Therefore, it was agreed that the Final Report dated August 1, 2001 is now used as an Interim Repot. Below is the Final Report to which the three volumes of the above mentioned book should be attached as Appendix.

This period is used only to complete the last remaining technical activity that was carried out by the group of T. Itoh in the area of Active Integrated Antennas based on GaN transistor.

With completion of this GaN project, all technical activities under this MURI program has been complete.

High Performance AlGaN/GaN HEMT Power Amplifier

I. Specific Aims

Our main objectives are to develop and demonstrate high performance AlGaN/GaN HEMT power amplifier structures for high power and high efficiency applications such as radar systems. Especially in order to enhance power amplifier efficiency while keeping high output power and associate gain, we demonstrate a novel power amplifier structure, in which AlGaN/GaN HEMT is integrated with antenna as both a frequency dependent output load and a radiator using an active integrated antenna (AIA) design approach that has been developed at UCLA. The AIA design method provides more design degree of freedom from the antennas to have certain antenna radiation characteristics such as harmonic termination.

II. High Efficiency AlGaN/GaN HEMT Power Amplifier Integrated with Antenna

An AIA can be considered as an active microwave circuit in which the output or input port is free space instead of a conventional 50-• interface. The antenna is not only used as a radiating element but also provides various circuit functionality such as filtering and harmonic tuning, and is an integral part of the microwave circuit design. This results in a functional compact design, eliminating the effect of any cable and feed line loss that would affect overall system efficiency and power if an external antenna was used. Especially it has been demonstrated to be an effective method for enhancing the efficiency of power amplifiers based on the characteristics of an antenna with harmonic termination characteristics instead of using output matching networks with harmonic termination parts such as power amplifiers in class-F operation with 2^{nd} and 3^{rd} harmonic terminations.

Circular sector microstrip antennas offer many attractive features including compactness, lightweight constructions, low cost, and ease of fabrication. Besides of these advantages, the most interesting antenna characteristic is no radiation power at higher order harmonics of the fundamental frequency. Due to the antenna characteristics, output harmonics are terminated by the circular sector antenna itself without additional output matching networks. A circular sector antenna was designed and fabricated on duroid substrate with dielectric constant of 2.33 and thickness of 0.775 mm at the resonant frequency of 2.45 GHz. The fabricated antenna was combined with AlGaN/GaN HEMT fabricated on SiC substrate through device isolation, ohmic metallization, gate metallization, Si_3N_4 passivation, and air-bridge processes. The PA was designed at fundamental frequency including a circular sector antenna as a part of the output matching network. The input matching network was fabricated on Alumina with dielectric constant of 9.8 and thickness of 0.375 mm. In practice, we have also considered the effect of Au bonding wires with equivalent inductance of 0.5 nH/mm to connect circuit components. The photograph of the fabricated the antenna integrated PA is shown in Fig. 1.

Measurements were done in an anechoic chamber based upon the Friis transmission equation (1). Radiated power from a passive antenna was measured in the broadside direction. Then, the passive antenna was replaced by PA with antenna and the measurement was repeated for determining all PA performances.

$$P_{rec} = (1 - |\Gamma_{trans}|^2) G_t \frac{P_{in}}{4\pi R^2} (1(1)|\Gamma_{rec}|^2) \frac{\lambda^2}{4\pi} G_r$$

In equation (1), P_{rec} and P_{in} are received power and input power from the output of HEMT to antenna and •$_{trans}$ and •$_{rec}$ are reflection coefficients of transmitting and receiving side, respectively. G_t and G_t are transmitting and receiving antenna gain and *1/4•* R^2 presents free space loss. This allows us to get the output power just before the antenna after de-embedding the receiving and the passive antenna gain.

Large-signal measurements of the antenna integrated PA were performed using a microwave synthesizer in conjunction with a microwave amplifier as a power source. The bias voltages were set to V_{ds} of 18 V and V_{gs} of -2.8 V at 2.45 GHz. Fig. 2 shows the measured output power, associate gain, and PAE versus input power. A peak PAE of 55 % at an input power level of 19 dBm, output power of 30 dBm, and power gain of 14 dB were obtained.

Harmonic terminations reduce radiating power at harmonic frequencies and increase PAE. It is observed through measured radiation patterns of 2nd and 3rd harmonic frequencies shown in Fig. 3 for E- and H-plane, respectively. Note that the radiation power at fundamental frequency of 2.45 GHz is normalized to 0 dB. Due to harmonic termination characteristic of a circular sector antenna, radiation powers at 2nd and 3rd harmonic frequencies are below -30 dB and -20 dB, respectively for each polarization in broadside direction.

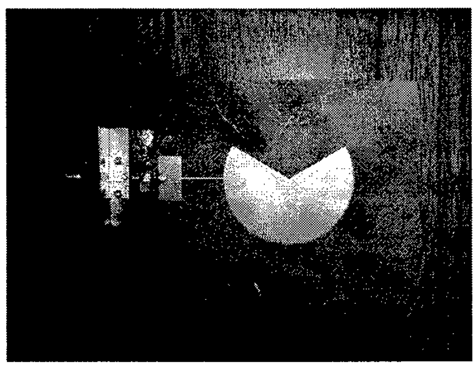

Fig. 1 Photograph of AlGaN/GaN HEMT PA integrated with circular sector antenna

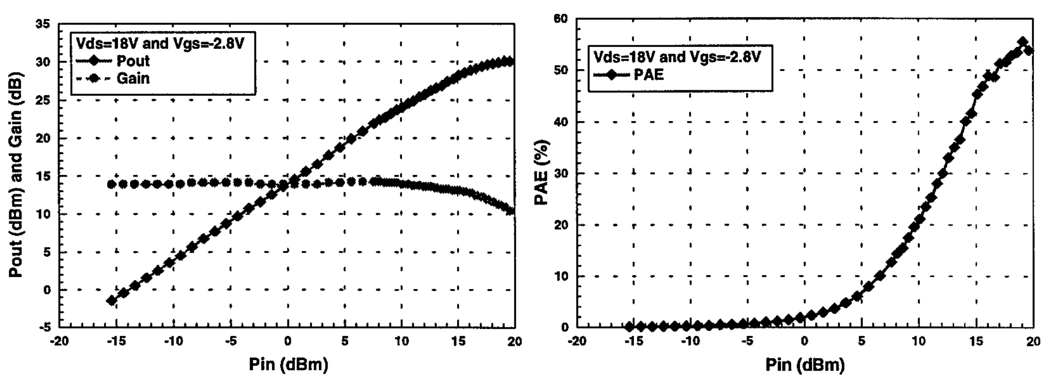

Fig. 2 Measured output power, gain, and PAE performances for AlGaN/GaN HEMT PA integrated with circular sector antenna (Frequency: 2.45 GHz)

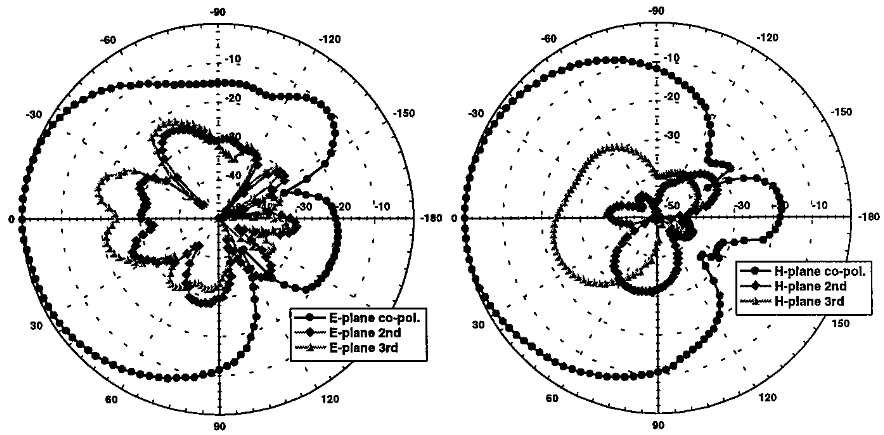

Fig. 3 Measured normalized E- and H-plane radiation patterns of the AlGaN/GaN HEMT PA integrated with circular sector antenna at fundamental, 2nd, and 3rd harmonic frequencies

Publications

1. Y. Chung, C.Y. Hang, S. Cai, Y. Qian, C. P. Wen, K. L. Wang, and T. Itoh, "Output harmonic termination techniques for AlGaN/GaN HEMT power amplifiers using active integrated antenna approach," To be presented in *IEEE MTT-S Int. Symp.* 2002, Seattle.